



Title of Investigation:

Oriented Nanocomposite Extrusion (ONE)

Principal Investigator:

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Other In-house Members of the Team:

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Other External Collaborators:

Hugh Bruck, David Bigio, and Arun Kota (University of Maryland-College Park)

Initiation Year:

FY 2003

Aggregate Amount of Funding Authorized in FY 2004 and Earlier Years:

\$105,000

Funding Authorized for FY 2005:

\$82,500

Actual or Expected Expenditure of FY 2005 Funding:

In-house: \$35,000; Grants: \$45,000 to the University of Maryland-College Park;
Procurement: \$2,500

Status of Investigation at End of FY 2005:

To be continued in FY 2006 with outside funding sources

Expected Completion Date:

TBD

DDF annual report

Purpose of Investigation:

Oriented carbon nanotube (CNT) composites should be able to achieve orientable, mechanical strengths that are 4 to 50 times greater than substrate material. They also should be able to reduce vehicle weight and costs. Further, use of CNT composites would give projects longer lifecycles, thermal delocalization, and selectable electromagnetic shielding/polarization. By quantifying composite properties and fabrication processes for oriented CNT composites of various substrates, a knowledge base will be created for future work on scaling-up fabrication and tailoring/enhancing composite properties for mission-specific applications. A long-term goal of this work is to transfer technology to industry by way of patent licensing through the Goddard Commercialization Office.

Accomplishments to Date:

The initial investigation was broken into three distinct, but complementary tasks: 1) rheometric measurements of Multiwalled Carbon Nanotube (MWNT)-loaded polymers at temperatures near their processing temperature; 2) computational fluid dynamics (CFD) to size the initial microchannel cross-section and guide design of the microchannel extrusion die; and 3) design and fabrication of the extrusion die and die-housing.

Rheometric measurement of 3–5 MWNT-loaded polymer samples was conducted, resulting in the identification of a variety of polymer substrates, which may be appropriately employed in this investigation. Based upon rheometric investigation of MWNT-loaded polymers within the 1–25 percent, by weight, range; microchannel cross-sections and aspect ratios also were optimized for extrusion. Identification of a novel shear-thickening phenomena, negative normal force, and exponentially accelerating viscosity curve resulted from the rheometric and process studies of MWNT-loaded polymers, in the 5–15 wt percentage-loading range.

Extensive Navier-Stokes CFD was conducted to solidify parity of actual MWNT-loaded polymer viscosity, while qualifying conceptual die designs. In addition, Knudsen number analyses were conducted for each candidate polymer to verify appropriateness of the no-slip assumption inherent to the Navier-Stokes flow-model. A three-dimensional Lattice-Boltzmann CFD (LB-CFD) code was developed using MATLAB, which successfully qualified the channel sizes and melt viscosities suggested to be of potential value by the Navier-Stokes CFD discussed above. The LB-CFD was developed as a qualifying model to a two-phase, *in situ* study of alignment of MWNTs flowing through microchannels with incrementally varying cross-section. This investigation's substrate viscosity tolerance, MWNT-loading range, and extrusion die metrics were successfully bounded through closed-form Navier-Stokes analysis, and verified through Navier-Stokes and Lattice-Boltzmann FEA simulation. Empirical validation of the workable, melt-viscosity process ranges are ongoing; however, uniform composite properties and extrudate dimensional enhancements are being realized regularly.

Design for fabrication of flexible and scalable microchannel dies by outside vendors has been established. The design of the microchannel die housing and twin-screw extruder (TSE) interface is complete.

Planned Future Work:

Recent progress on the fabrication and characterization of Oriented Nanocomposites via a scalable twin-screw extrusion process has made it practical for us to discuss scale-up and spin-out of fabrication hardware design and process technologies with industry partners, including Spartech Corp., Clayton, Missouri. This will facilitate development of macro-scale (meter-wide) production of commercial-off-the-shelf (COTS) composites to support a variety of missions Agencywide. The performance and capability improvements of oriented CNT composites over current material capabilities are dramatic. CNTs have an axial modulus >1 TPa, allowing their composites to be potentially stronger than steel in tension, yet flexible with near infinite life. CNTs axially conduct heat at $>3,000$ W/mK and electricity 6 orders-of-magnitude better than copper, allowing their composites to de-localize any concentrated heat source and behave as ballistic electrical conductors. Current mission-infusion opportunities for oriented CNT composites include multifunctional and in-flight repairable skins and structure for the Crew Exploration Vehicle, inflatable habitats for the moon and Mars, sunshields for a variety of missions including the James Webb Space Telescope, and next-generation extravehicular activity suits. A CNT film could rapidly redistribute the heat load, resist puncture, and arrest propagation of any tear as it develops. It also has potential to be further functionalized as a layerable radiation-shielding material for interplanetary proton events and emergency shelters for the Moon and Mars.

The major challenge is demonstrating a new design paradigm to progress from the 3-inch wide samples we've produced using an etched silicon-die to the ~ 1 foot wide demonstration proof that Spartech and others would require to iterate to meter-scale production.

This proposal addresses the challenge of scale-up through the fabrication design of parallel, interdigitated plates about 1-foot in width. These may be defensibly iterated for meter-scale fabrication of composite-laminate layers of continuous length. David G. Pocost, Executive Vice President for Technology Development at Spartech Corp., has agreed to work closely with our design and development team to insure that our ~ 1 foot wide microchannel die can be directly leveraged for integration into its new \$50 million twin-screw extrusion R&D facility in Richmond, Indiana. Project objectives include:

- Develop a new design regime for ~ 1 -foot wide microchannel dies.
- Characterize best practice manufacturing techniques and assess interface/integration considerations for spin-out of ~ 1 -foot microchannel die composite production.
- Collaborate with Spartech Corp. and others to ensure defensible meter-scale scale-up of selected design and manufacturing methodology and to establish qualified COTS partnership development to enable future NASA missions.

Key Points Summary:

Project's innovative features: Identifying a novel two-phase, shear-thickening behavior, developing a scaleable nanocomposite production process, and verifying multifunctional composite material properties against literature are among the project's innovative features.

Potential payoff to NASA/Goddard: Benefits include standardization of advanced composite manufacturing through the licensing of these processes to industry; cost and system mass re-

ductions because we replace graphite epoxy and other materials with robust, lightweight, high-strength nanostructured composites; and support for a broader scope of missions because of the availability of high- performance, multifunctional, nanostructured composites.

Criteria for success: The criteria for success include development of a macroscale fabrication process for multifunctional nanostructured composites; production of macroscale nanostructured composites; characterization and verification of multifunctional material property enhancements against state-of-the-art as presented in literature; and development of a technology transfer for scale-up and commercial-off-the-shelf development with an industry partner.

Technical risk factors: They include production equipment failures; melt-formulation viscosity limitations on process control; production equipment procurement and fabrication limitations; original equipment manufacturing production delays and failures; and composite characterization methodology, and instrument availability challenges.